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Identifiability Evaluation of Crucial Parameters for Grid Connected Photovoltaic Power Plants Design Optimization

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ABSTRACT This paper aims to assess the impact of different key factors on the optimized design and performance of grid connected photovoltaic (PV) power plants, as such key factors can lead to re-design the PV plant and affect its optimum performance. The impact on the optimized design and performance of the PV plant is achieved by considering each factor individually. A comprehensive analysis is conducted on nine factors such as; three objectives are predefined, five recent optimization approaches, three different locations around the world, changes in solar irradiance, ambient temperature, and wind speed levels, variation in the available area, PV module type and inverters size. The performance of the PV plant is evaluated for each factor based on five performance parameters such as; energy yield, sizing ratio, performance ratio, ground cover ratio, and energy losses. The results show that the geographic location, a change in meteorological conditions levels, and an increase or decrease in the available area require the re-design of the PV plant. A change in inverter size and PV module type has a significant impact on the configuration of the PV plant leading to an increase in the cost of energy. The predefined objectives and proposed optimization methods can affect the PV plant design by producing completely different structures. Furthermore, most PV plant performance parameters are significantly changed due to the variation of these factors. The results also show the environmental benefit of the PV plant and the great potential to avoid green-house gas emissions from the atmosphere.

INDEX TERMS Levelized cost of energy, Optimum configuration, Design optimization, PV grid-connected, Large-scale PV power plants, Crucial parameters.

I. INTRODUCTION

At present, large-scale photovoltaic (PV) power plants represent the highest rate of power investments compared to conventional power generation and renewable energy sources such as wind power. Additionally, the penetration rate of large-scale PV power plants is growing quickly, including small PV power plants [1]. On the one hand, the cost of PV power plants is promising due to the intrinsic qualities of the system compared to other renewable energy sources, limited maintenance requirements, reduced service costs, reliable, noiseless, and easy to install [2]. On the other hand, there is continuous improvement in the conversion efficiency for crystalline silicon (c-Si) and thin-film cadmium telluride (CdTe) PV modules [3], [4]. In 2019, the photovoltaic energy increased with a capacity of around 115 gigawatts. The statistics show that the PV market increased from a capacity of 23 gigawatts in 2009 to 627 gigawatts in 2019. Furthermore, solar energy is expected to become the most installed source of energy in the world by 2050 [5].

Despite the environmental benefits of photovoltaic power generation, technical and economic issues arise if not designed properly. Regarding technical issues, the PV array oversizing could have negative impacts on the PV inverter reliability and lifetime, since the rating power of the PV arrays is higher than the inverter rating power [6]. Besides, the sizing ratio R_s is usually less than one and has a typical value in the range of $1 \leq R_s \leq 1.5$, which varies with the installation fields. Thus, choosing the right type of PV module and inverter to meet the different design requirements of the large-scale PV power plant has a significant influence on optimum performance of the PV power plant. Moreover, the shading area has an important impact on the output power of the PV module and leads to a decrease in energy generation if not taken into account. Regarding the economic issues, PV array oversizing leads to a high cost of energy due to the extra maintenance and installation costs. Furthermore, since the amount of solar irradiance reaching the large-scale PV power plant cannot be changed, an optimal PV module tilt angle should be addressed to extract the maximum amount of energy using the appropriate components to forecast the energy generation reliably. In light of this, an optimal combination between PV arrays and inverters should be addressed, and the optimal distance between adjacent rows to avoid mutual shading is mandatory in the design process. Therefore, it is important to design large-scale PV power plant grid-connected to meet optimum performance and ensure maximum lifetime and reliability of the components and, maximize the harvested energy with the lowest associated costs.

In Spain, Fernández-Infantes et al. introduced a computer application and parameters to optimally design the PV power plant connected to the electric network [7]. The shading analysis to avoid any shadow effect on PV modules surface, PV array losses, wire losses, inverter size, PV module tilt angle, and orientation have been employed to calculate the yearly energy generation. Moreover, the financial analysis is taken into account by using the discount rate, sold energy, annual inflation, costs, and taxation. Furthermore, the environmental analysis was considered by computing the pollution. However, the size of the inverter was selected by intuitive consideration in this method, and the optimization process neglected the PV array size. The PV power plant grid-connected optimization has been presented in [8]. This study aims to optimally select the PV modules and inverters type, optimal PV modules tilt angle, their arrangement within the PV plant installation area, and their optimal distribution among the inverters using real meteorological data.

The optimization procedure maximizes the total net present value (NPV) of a PV power plant project by an iterative simulation based on a genetic algorithm (GA). A methodology for the optimal design of grid-connected PV power plants considering the economic analysis was introduced in [10]. The best solution was explored using the particle swarm optimization (PSO) approach based on a multi-objective optimization problem to design the PV power plant. This study aims to identify the best arrangement of the components with maximum economic and environmental benefits during the PV plant lifetime. The design variables are the optimal placement of the PV modules within the installation field and their distribution among the inverters, optimal tilt angle, inverters, and PV module's optimal number. In 2013, Kerekes et al. proposed a new methodology to optimize large-scale PV power plants [11] using a GA. However, the levelized cost of energy (LCOE) analysis was included to enhance the new method performance as well as the economic analysis, internal return rate, and the payback period was discussed. The work in [12] introduced a methodology to design PV power plants grid-connected using high time resolution of one min average values of the solar irradiance and ambient temperature input data. The best solution was explored using the master-slave algorithm and dynamic demes algorithm approaches. The research aimed to achieve the maximum economic profit of the PV plant during the PV module lifetime.

The work in [13] suggested an optimization approach for the economical design of PV power plants using the specifications of the inverter. The aim of the study is the improvement of LCOE, which considers the notion of availability of a large-scale PV power plant during its life cycle. According to this study, the conventional LCOE index determines the central topology to minimize the produced energy cost. An improved algorithm is provided based on effective LCOE, and a multi-string topology, despite higher investment cost, becomes the economically winning topology. The authors suggested an economical size of inverters for 0.1–100MW PV power plants range from 8 to 100 kW, which means multi-string topology. A methodology proposed in [14] sought to optimize the PV power plant configuration and to provide an economic analysis study. The optimum design divides into two stages. The first stage is the design procedure using different optimization techniques, and the second stage is based on the economic analysis of the PV power plant, using the Monte-Carlo simulation. PV power plant size optimization is presented in [15]–[17]. The design process takes into consideration the environmental data and the commercially available components such as PV modules and inverters. A co-design technique was proposed in [18] to investigate the optimal selection and configuration of PV arrays to meet the structure of the inverter for the maximum annual energy generation of the PV grid-connected using the PSO algorithm. According to the authors, the developed co-design optimization technique can achieve the maximum in the power production of a grid-connected PV system compared to the case designing PV arrays and inverters separately. A recent study in [19] presented a methodology to design PV plants to reduce installation, maintenance, and operation costs. This framework details the semi-hourly step time of meteorology data of the selected the location and analysis of the specifications of different PV plant components to determine the optimum PV module and inverter along with the suitable topology for the selected location. The mathematical model considered the minimization of the cost of energy production and the maximization of the annual energy generation. The grey wolf optimizer-sine cosine algorithm was applied for this purpose, and the results showed that it was possible to obtain good solutions with this approach. A review study for large-scale PV power plant topologies is presented in [20]. Additionally, review papers for grid-connected PV system optimization and challenges are presented in [21]–[26].

The focus of the previous studies is mainly related to the methodology side by proposing an optimal design, sizing and configuration of PV power plants grid-connected. In this paper, the method for the design optimization of large-scale PV power plants, which has been presented in [16], is extended. However, a comprehensive study on the effect of nine crucial key factors variation on eight important optimal design variables and five performance parameters of the PV power plant is not presented anywhere. In addition, this research presents an environmental impact of the PV power plant. Technical and economic issues can be faced such as energy losses caused by the shading effect between adjacent PV rows, the optimum combination between the PV array-inverter to avoid oversizing and the financial risks due to the high cost of energy, especially in the case of the crucial key factors variations.

The main contributions of the paper can be summarized as follows:

1. The effect of nine key factors variation on the initial PV power plant optimum configuration is investigated, considering each factor individually.
2. The evaluation of the PV power plant based on five important performance parameters is examined for each key factor.
3. The correlation between the crucial key factors variation and the PV power plant main performance parameters based on eight important design variables is presented.

II. MAIN COMPONENTS OF GRID-CONNECTED PV POWER PLANTS

Regardless of the topology of grid-connected PV power plants, it consists of four main equipment. The overall configuration of a grid-connected PV power plant is illustrated in Fig. 1. The first component is a PV array generator that transforms sunlight to direct current (DC) power. It consists of large numbers of PV modules connected in series and parallel. The second device is the three-phase inverter used to convert the generated (DC) power from PV arrays to high-quality alternative current (AC) power. Additionally, the LCL filter component plays an important role in suppressing the switching harmonics of the output alternative voltage and current generated by inverters. Finally, to evacuate to energy generation by the PV power plant grid-connected, a step-up transformer is required to meet the same electric grid voltage level at the point of common coupling and to ensure galvanic isolation.

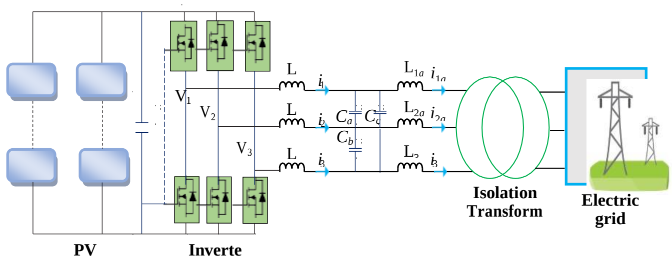

FIGURE 1. **Main components of grid-connected large-scale PV power plants [27].**

III. DESIGN PARAMETERS OF PV POWER PLANTS

This section discusses each decision variable, including its importance in the design process of large-scale PV power plants. In this methodology, the decision parameters to be computed by the suggested approaches are eight variables to meet the technical and economical design requirements of the large-scale PV plant. They are:

1. Depends on the PV inverter size and the selected PV power plant configuration, the total number of PV modules connected in series (N_s) and parallel (N_p) in each string must be calculated by the optimization process according to the electrical specifications of the inverter in terms of voltage and current. In certain locations with low ambient temperature profiles, the overvoltage can lead to inverter damage. To solve this issue, the total number of series PV modules connections (N_s) should be determined in each string. Additionally, in locations with high solar irradiation profiles, the overcurrent may cause inverter damage. To overcome this problem, the total number of parallel PV modules connections (N_p) in each string has to be optimally computed.
2. The number of PV module lines in each row (N_r), is the third parameter. PV modules can be installed in multiple lines in each row with considering the width and height of the row. This configuration makes the design of the PV power plant more flexible and contributes to minimizing the cost.
3. For achieving a more efficient PV power plant design, the installation angle (β) is often considered at the first stage. In the PV power plant, the tilt angle is an important parameter for achieving maximum solar radiation falling on the PV modules. An optimal tilt angle and orientation maximize the solar irradiance on the PV array. Also, the optimum tilt angle for PV systems should be calculated accurately for each location to increase energy production and to reduce the

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cost of large-scale PV power plants. An increasing tilt angle requires more land due to the increase of the space between rows to avoid the shading effect. More occupied land leads to an increase in the length of the cables, which can affect the investment cost and increase the losses.

4. Sufficient space (F_y) between two adjacent rows in the large-scale PV power plant is highly recommended to avoid any shading effect that can reduce energy production significantly. The selected area to install the PV power plant should be sufficient to meet the required capacity since insufficient land leads to reduce the inter-row distance that causes high energy losses due to the significant number of rows in the PV power plant.
5. Two orientation options are given to install the PV modules (PV_{orien}). The objective function can be affected by the selected orientation, which can be vertically or horizontally.
6. A list of different PV modules (PV_i) and inverters (IN_i) have been employed in this methodology. In the end, only one optimal combination can be selected and represents the suitable components for PV system installation. The technical characteristics of these components are considered as well as their associated costs.

The vector of the design variables is summarized in the following equation:

$$X = \begin{bmatrix} N_s & N_p & N_r & \beta & F_y & PV_{orien} & PV_i & IN_i \end{bmatrix} \quad (1)$$

IV. FACTORS AFFECTING PV POWER PLANT DESIGN

This section details the key factors that can affect the optimized design of PV power plants, as illustrated in Fig. 2.

A. LOCATION

In this study, three different geographical locations have been employed to evaluate the impact of the location on the optimal PV power plant design parameters using the same components, available area and costs. The optimization process was carried out for different locations around the world. All selected sites have different characteristics, such as PV power plant coordinates, latitude, longitude, and different climate conditions. Algeria is located in the center of North Africa facing Europe between 35° and 38° of latitude north and 8° and 12° longitude east, with a total area of 2,381,741 km^2. Malaysia is situated on the South China Sea and located between 0°51 to 6°43 in North latitude and 99°38 to 119°16 in East longitude. The total surface is about 330,000 km^2 of which is made up of East and Peninsular Malaysia with 60% and 40%, respectively. Turkey is situated at the Mediterranean between 36° and 42° N latitudes and has typical Mediterranean weather with a total area of 783,562 km^2.

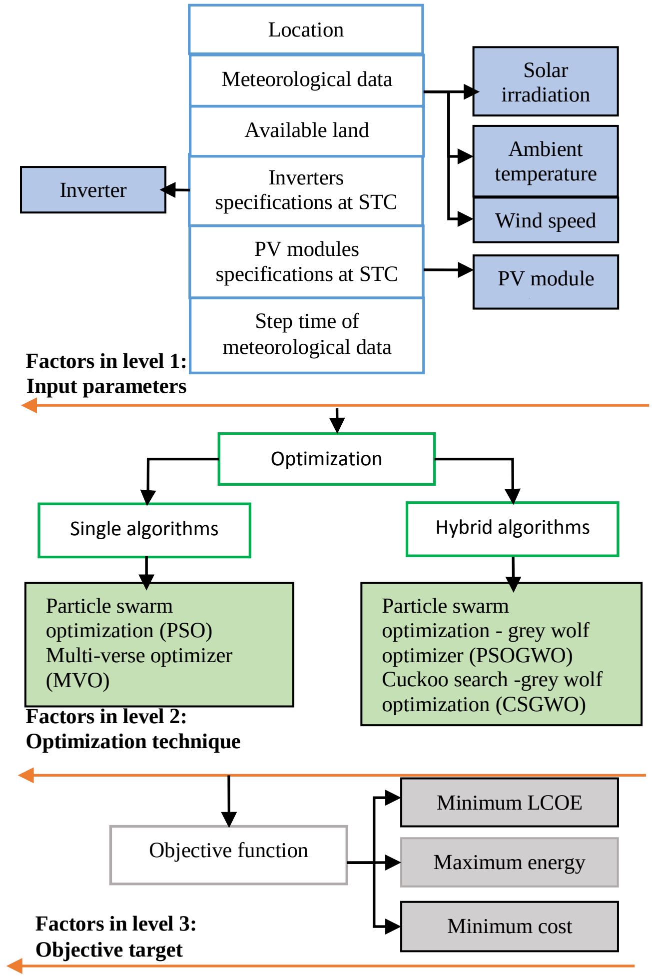

FIGURE 2. Key factors affecting the optimized design of PV power plants

The site choice is the early stage in large-scale PV power plant projects due to its high importance in the design process. Several factors can be considered to improve PV plant performance. In this regard, the PV power plant should be constructed located near urban areas to meet the high energy demand without affecting urban growth and city development. A short distance between the PV power plant and load is an advantage from an economic point of view to minimize the transmission line cost and reduces power losses. Furthermore, the transmission line capacity should be close to the PV plant output power. Additionally, the selected site with a short distance from main roads and railway facilities is important to reduce the construction cost of the PV power plant and the transport cost of a large number of components. Easy access is also important to avoid the construction cost of the road and for maintenance purposes in the future. Moreover, the proximity of the PV plant to substations is highly recommended to receive the PV power plant generated energy and also due to the high construction cost of new substations. Furthermore, the selected PV power

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plant site should have sufficient water resources to ensure the cleaning of PV arrays at least twice a month to increase their performance.

B. METEOROLOGICAL DATA

In this research, the large-scale PV power plant is evaluated under different climate conditions by the variation in solar irradiance, ambient temperature, and wind speed levels. The reason behind this variation in meteorological data of the installation area is to investigate the impact of such key factors on the optimum design parameters of PV power plants grid-connected, and at which variation level the design is affected. In other words, to find at which level of variations the PV power plant should be re-designed. Besides, to demonstrate the impact of the variations of these three key factors on the optimized design of PV power plant independently.

1) SOLAR IRRADIANCE

Several published studies quote solar irradiance as a critical factor indicating the potential areas for large-scale PV power plant construction. Solar irradiance has a significant effect on the large-scale PV power plant performance since it is considered a variable source of energy because it changes from time to time. Additionally, direct and diffuse radiation are the main components of solar irradiance received by a surface. The amount of harvested energy depends mainly on the solar irradiance reaching the area where the PV power plant is installed. In light of this, to make the PV plant economically viable, areas receiving significant solar radiation are suitable for building a large-scale PV power plant. Accordingly, the proper design of a PV power plant should take into account the variation of solar radiation in the installation area.

Algeria is a Mediterranean country with the largest solar energy potential, according to the German Aerospace Centre (DLR). The average annual duration of solar radiation is more than 2000 hours in high plains and reaches 3900 hours in the big Sahara [28]. During one year, the energy obtained on a horizontal surface of 1 m^2 is very high, with 2263 kWh/m^2 in the south and 1700 kWh/m^2 in the north [29]. Malaysia receives and abundant solar irradiance for about 10 hours per day. The daily average is estimated at 4.21-5.56 kWh/m2/day [30]. Based on its geographical location, Turkey has a strong potential for solar energy. The average annual duration of solar irradiance is equal to 2738 h. Turkey receives an average solar irradiance duration of about 7.5 hours per day. Solar energy is considered as a strong potential renewable energy in Turkey [31].

2) AMBIENT TEMPERATURE

The ambient temperature represents the second meteorological factor used for designing large-scale PV power plants. It is well-known in the existing literature that the PV module's efficiency can be affected by the ambient temperature, which can decrease the PV system performance. It is more suitable to install large-scale PV power plants in areas with a lower temperature to increase the output power of PV modules. The highest PV module temperature leads to a decrease in the PV power plant energy generation. Hence, the PV power plant can produce more energy in a location with lower temperatures compared to hot areas, even though the degree of solar radiation is the same. For those reasons, the correct design of large-scale PV power plants should take into consideration the variations in ambient temperature in the installation field.

3) WIND SPEED

Wind speed is another important meteorological factor, and it is measured in meters per second (m/s). In a large-scale PV power plant, the wind speed affects PV modules output power. In the case of high speed at the PV plant installation area, dust can accumulate on the PV modules' surface, thereby damaging them by disarranging the PV modules' orientation. Wind speed can also affect the energy generation of the PV power plant. However, in favorable conditions, wind speed can contribute to cooling the PV modules and decreasing their temperatures. Therefore, for the correct design of a PV power plant, the wind speed variation has to be included since it affects the PV module's efficiency.

C. AVAILABLE LAND

The available land used for installing the large-scale PV power plant should be sufficient to meet the capacity requirements. High PV power plants' installed capacity leads to increasing the occupied land since the installed capacity is proportional to the area.

In this methodology, two alternatives are provided for properly designing PV power plants. The first option is to set the PV plant installed capacity as input data, and the optimum design solution should be achieved for the given capacity. In the case of the available land is big enough, the designer will face difficulty predicting if the given capacity is suitable for the available area. In the second option, the designer could set the available area as an input value based on the surface of the installation site without needing to set the installed capacity. More importantly, for reducing the occupied area by the PV power plant, it is highly recommended to use PV modules with high conversion efficiency and less size, which can also decrease the cost of the land.

The variation impact of the available land on the optimum design parameters of grid-connected PV power plants is investigated. The area variation can be achieved by reducing or increasing the available land. The reason behind this variation is to show the correlation between the area and the PV plant optimum design. The available land variation can be required anytime before or after installing the PV plant.

D. PV MODULES AND INVERTERS

The inverter topology used in large-scale PV power plants has no relation with the area occupied and the number of PV modules installed, but the inverter topology used can affect

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the overall dimension of the large-scale PV power plant. Two alternatives can be used, such as central structure and string layout. The impact of the inverter topology on the design parameters of the PV power plant was investigated in [32]. However, in this study, central topology with different inverters size is considered. The list of inverters used in the optimization process is shown in Table I.

The material utilized in the PV modules makes a big difference in the area occupied and total energy production [16]. Also, improved materials of PV modules play an important role in reducing the area used by large-scale PV power plants. PV modules designed with less size and higher capacity have to be developed specifically for large-scale PV power plants. The aim is to help designers reduce the costs of the PV power plant installation and the occupied area. In the case of using the same rated power, if the PV module conversion efficiency decreases, the land occupied by the large-scale PV power plant increases. The area used is not the only factor that affects the total cost but also the installation cost of a PV power plant, transportation of different components, maintenance of the system, and mounting characteristics. The list of PV modules used in the optimization process is illustrated in Table II.

E. OBJECTIVE FUNCTION

The design problem of the large-scale PV power plants can be stated in a general mathematical form using different objective functions. In the case of single optimization algorithms, the objective function can be used for minimum or maximum value. In the PV power plant design optimization, the objective function can be used for technical, economic, and environmental evaluation. In this study, the use of three different objective functions for designing a PV power plant is considered to examine the impact of the variation of the objective function on the design parameters of the PV power plant. Such analyses lead to evaluating the overall dimension of the PV plant in terms of structure, components distribution, and arrangement within the available area.

In this context, minimum LCOE, maximum energy generation, and minimum cost are set as objective functions to select the optimal candidates for designing the PV power plant and to find its optimal structure as a global solution.

The first objective function can be defined as the total cost of the PV plant over its lifetime, and it can be calculated according to the sum of the maintenance C_c, operations, and installation costs C_M of the PV plant. Total cost is given in the following expression:

$$C_{tot} = C_c\left(X\right) + C_M\left(X\right) \tag{2}$$

The second objective function is set as the total amount of energy captured from the PV plant during its lifetime. The maximum annual energy is calculated based on the output power P_{plant} and it is expressed by the following equation:

$$E_{year} = P_{plant}\left(X\right) n_s EAF \tag{3}$$

where n_s is the PV plant operational lifetime, n_s equal to 1 and EAE is the energy availability factor.

TABLE I
INVERTERS SPECIFICATIONS AT STC

Specification	Unit	INV1	INV2	INV3	INV4	INV5	INV6
Nominal power (P_i)	kW	50	500	630	875	1645	1732
Minimum input voltage ($V_{i,min}$)	V	250	450	525	525	550	580
Maximum input voltage ($V_{i,max}$)	V	950	1100	1100	1100	1000	1000
Maximum MPPT voltage($V_{i,mppt,max}$)	V	850	825	825	825	850	850
Power loss ($P_{i,sc}$)	W	1.5	490	490	650	1800	1800
Efficiency (η_{inv})	%	0.975	0.986	0.986	0.987	0.985	0.985

TABLE II
PV MODULES SPECIFICATIONS AT STC

Specification at STC	Unit	PV1	PV2	PV3	PV4
Nominal maximum power ($P_{mpp,stc}$)	W	280	285	295	335
Optimum operating current ($I_{mpp,stc}$)	A	8.95	9.02	9.22	8.96
Optimum operating voltage ($V_{mpp,stc}$)	V	31.3	31.6	32	37.4
Current temperature coefficient (K_i)	(%/C)	0.0003	0.0005	0.0003	0.0005
Voltage temperature coefficient (K_v)	(%/C)	-0.0029	-0.0032	-0.0029	-0.0031
Open circuit voltage ($V_{oc,stc}$)	V	38	38.3	38.5	45.8
Wind speed temperature coefficient (K_r)	-	1.4684	1.4684	1.4684	1.509
Length ($L_{pv,1}$)	m	1.65	1.65	1.65	1.96
Width ($L_{pv,2}$)	m	0.992	0.992	0.992	0.992
Efficiency	%	17.1	17.4	18	17.23
Type	-	Mono	Poly	Mono	Poly

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The minimum LCOE is the third objective function that is obtained by dividing the PV plant total cost C_{tot} by the total energy production E_{tot} during its operational lifetime, which is 25 years. LCOE is calculated according to the following equation:

$$LCOE = \frac{C_{tot}\left(X\right)}{E_{tot}\left(X\right)} \tag{4}$$

F. OPTIMIZATION TECHNIQUES

An optimization algorithm can show good performance with promising results in solving an optimization problem, but the same algorithm may provide low performance on another. In this context, several recent algorithms have been applied in this methodology to highlight their effect on the PV power plant's optimal design parameters. However, the optimization techniques used are single and hybrid with single objective function including, multi-verse optimizer (MVO) [33], PSO [34], hybrid particle swarm optimization and grey wolf optimizer (PSOGWO) [35], and hybrid cuckoo search - grey wolf optimization (CSGWO) [36].

Design optimization techniques can be divided into classical approaches and modern approaches. Classical approaches use differential calculus for finding the optimal solution. Modern approaches use artificial and hybrid techniques. These approaches have better performance, high convergence, and provide more accuracy in solving the problem. The design of a large-scale PV power plant is complex due to the variation of weather conditions, nonlinear operating of the PV system, constraints related to the components as well as the location of the installation site. Therefore, in recent years, modern methods based on meta-heuristics techniques have widely been applied.

Design optimization techniques can use single and multi-objective optimization functions. Single objective optimization can find the minimum or the maximum value of the objective function, and multi-objective optimization is the combination of more than one individual objective function. The majority of classical approaches used single techniques with a single objective optimization function. Modern approaches use both single and hybrid techniques for solving individual and multi-objective optimization problems.

Single optimization techniques are simple, easy to implement and show relatively fast convergence and accuracy in finding the optimal solutions. However, as grid-connected PV power plants are quickly growing, there is a need for highly effective algorithms in seeking the optimum global solution. Therefore, hybrid algorithms have been developed to achieve high performance in solving a given problem. The hybrid approach combines two or more single optimization approaches. This combination aims to benefit from the complementary characteristics of the approaches to solve complex design problems. The design of large-scale PV power plants is always based on the estimation of the system size and configuration in which involves several factors and a considerable number of components. In light of this, designers can increase the system profit using the same components by using new optimization algorithms with high performance.

G. STEP TIME OF METEOROLOGICAL DATA

The step time is the period between two measurements on meteorology data for the same location. The shorter the measurement period, the more accurate the meteorological data. In PV systems, the peaks and troughs of the meteorological data cannot be achieved using the daily or monthly average of solar radiation, wind speed, and ambient temperature. Using such measurement data to design large-scale PV power can increase the associated financial risk, and may lead to oversizing the PV system.

The impact of the step time resolution on the PV power plant design was investigated by using semi-hourly step time data and hour-by-hour data for one year in a recent study presented in [19]. Using semi-hourly step time meteorology data results in improving the PV power plant LCOE and increasing the financial benefit. The measurement data volume using a one-hour step time series is 8760 and is equal to 17520 for semi-hourly step time.

V.PERFORMANCE MODELING

To evaluate the grid-connected PV power plant performance, different parameters were studied like LCOE ($/kWh), AC output energy (MW), sizing ratio (Rs), performance ratio (PR), ground cover ratio (GCR), energy losses (MW) and green-house gases (GHG) emissions reduction (tons). These parameters were used to perform the electrical analysis of the PV plant linked to the variation of different factors affecting the PV plant optimized design and performance.

A. ENERGY OUTPUT

The total energy production of the PV power plant during its operational lifetime can be determined based on equation (5). Besides, the total hourly, daily, monthly and yearly energy generation by the PV power plant can be also obtained using a specific period, for instance, if n_s is equal to 1, the total yearly produced energy is obtained.

$$E_{tot} = P_{plant}\left(t\right) n_s EAF \tag{5}$$

B. SIZING RATIO

The PV array rated power $P_{PV(rated)}$, over the inverter rated power $P_{i(rated)}$ under standard test conditions, is commonly used to define the PV system sizing ratio (R_s). The sizing ratio can be calculated according to the following equation:

$$R_s = \frac{P_{PV(rated)}}{P_{i(rated)}} \tag{6}$$

The nominal power of the PV array $P_{PV(rated)}$ can be obtained using equation (7).

$$P_{PV(rated)} = P_{mpp,stc} . N_s . N_p \tag{7}$$

where $P_{mpp,stc}$ is the PV module nominal maximum power at standard test conditions.

C. PERFORMANCE RATIO

The performance ratio is an efficiency index and a quality factor for grid-connected PV power plants, which evaluates the final energy yield (Y_f) with respect to the nominal yield (Y_r). Performance ratio permits the comparison of PV power plants independent of nominal rated power capacity, geographic location, PV module tilt angle, and orientation [37]. The performance ratio can be calculated by [38]:

$$PR = \frac{Y_f}{Y_r} \tag{8}$$

The final yield of the system (Y_f) is the ratio between the final energy output of the power plant to the nominal DC power.

$$Y_f = \frac{\text{Final energy output in kWh}}{\text{Nominal DC power in kW}} \tag{9}$$

The nominal yield (Y_r) can be defined as the ratio of total in-plane irradiance to the reference irradiance under standard test conditions (STC).

$$Y_r = \frac{\text{Total in plane irradiance in kW/m}^2}{\text{PV reference irradiance in kW/m}^2 \text{ at STC}} \tag{10}$$

It is evident from equation (10) that reference yield is dependent on geographic location.

D. GROUND COVER RATIO

Due to the PV module tilt angle difference between PV power plants, the ground cover ratio (GCR) is consequently different. The GCR ratio can be calculated as [39]:

$$GCR = \frac{A_{PV}}{A_{PV} + L} \tag{11}$$

where A_{PV} is the total PV area excluding land and $(A_{PV} + L)$ is the total PV area including land, additionally, A_{PV} is defined as:

$$A_{PV} = A_c . NI \tag{12}$$

where A_c is the PV module area in (m^2), NI is the total number of PV modules.

E. ENERGY LOSSES

The total PV power plant energy losses during its operational lifetime (25 years) are considered as the difference between the energy produced from PV modules (P_{PV}) and the total output power (P_{plant}) before its injection into the grid, including shading losses, components losses, AC and DC cables losses. PV power plant energy losses can be obtained using the following equation:

$$\sum P_{losses} = \sum P_{PV} - \sum P_{plant} \tag{13}$$

VI. ANALYSIS RESULTS AND DISCUSSIONS

A. LOCATION EFFECT

The geographic location impact on the PV power plant optimal design and performance was performed for different locations around the world, having completely different characteristics. The first location is Kuala Lumpur, the capital city of Malaysia, the second is Istanbul city in Turkey, and finally Illizi city in South Algeria.

TABLE III
OPTIMAL RESULTS FOR EACH LOCATION

Location	Africa (Algeria)	Asia (Malaysia)	Europe (Turkey)
N_s	23	24	19
N_p	98	195	131
N_r	3	5	4
β	20	11	26
F_y	1.526	1.419	2.610
PV_i	PV3	PV3	PV3
INV_i	INV4	INV5	INV3
PV_{orien}	1	1	1
LCOE ($/kWh)	0.0301	0.0372	0.0538
Yearly energy (MWh)	2876.24	2261.34	1616.13
Rs	0.75992	0.83927	1.1655
PR	0.871	0.838	0.802
GCR	0.40482	0.43925	0.38958
Yearly losses (MWh)	240.8513	191.146	205.7946

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The rated power of the PV plant is set 1.5 MW using the same available area, shape, costs, and same components such as PV modules and inverters. The optimal design is performed using hybrid cuckoo search-grey wolf optimization to minimize the PV power plant LCOE. Table III shows the optimum value of eight design variables for each location and the LCOE objective function obtained from the optimization process. According to the obtained results, the location has significantly affected the optimum design variables of the PV power plant. In that way, the optimum value of the PV power plant design variables can be achieved according to each location. The total number of series (N_s) and parallel (N_p) PV modules connections, the number of PV module lines in each row (N_r), the tilt angle (β), the inter-row distance (F_y), and the selected inverter (INV_i) result in different values. In contrast, the optimization process selected the same PV module type (INV_i) with vertical orientation (PV_{orient}) in all locations.

The LCOE of the PV plant for all locations presents different values. The variation in LCOE value depends mainly on the amount of solar irradiance received in each location that leads to high energy generation. The difference in LCOE values between these locations is affected by the PV power plant produced energy during its lifetime. LCOE is lower in two locations (Algeria and Malaysia) due to the significant available amount of solar irradiance compared to the other location (Turkey). Fig. 3 shows the monthly produced energy in the locations under study.

The optimal PV plant design in Africa (Algeria) presents the highest value of energy generation in March due to the high solar irradiation in this month, as illustrated in Fig. 4. It is observed that during all the year, the produced energy is high, which results in a low value of LCOE equal to 0.0301 ($/kWh). The PV plant generated energy in Asia (Malaysia) is high and close in terms of value during all seasons of the year and leads to 0.0372 ($/kWh) of LCOE. The harvested energy in Europe (Turkey) varies from one month to another since the received solar irradiance is low in the winter season and high in summer. The highest of generated energy is obtained in June whereas the lowest is in January. The low insolation in winter affects the cost of energy of the PV power plant and leads to a value of 0.0538($/kWh).

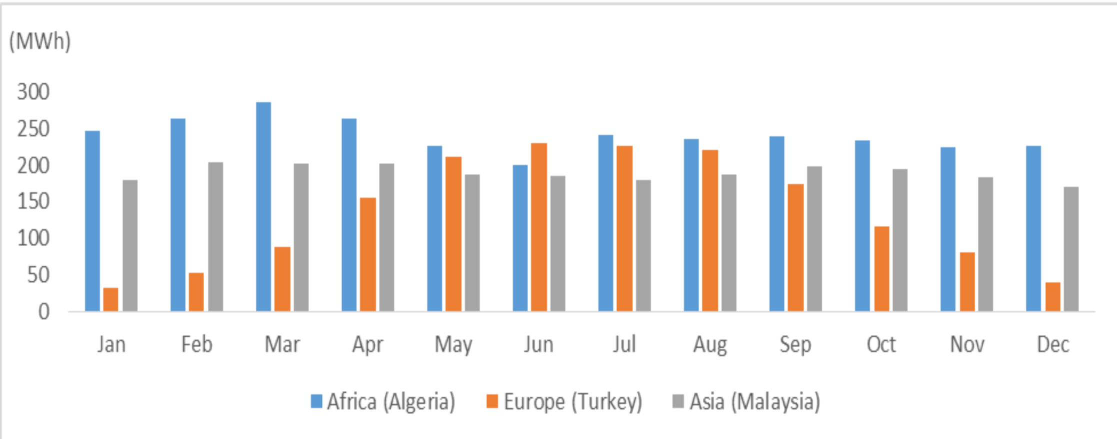

FIGURE 3. PV power plant monthly produced energy for all locations (MWh)

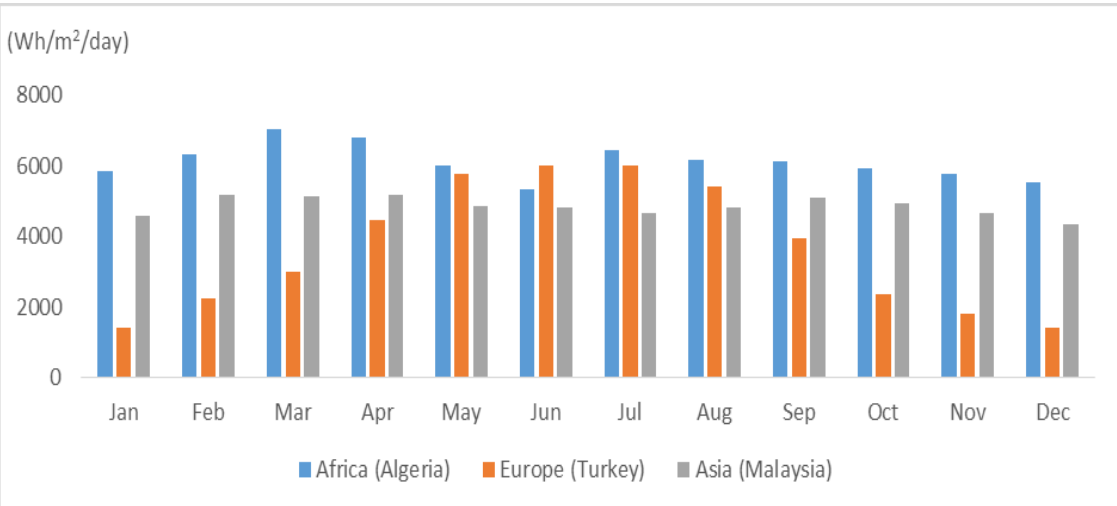

FIGURE 4. Monthly insolation for all locations (Wh/m²/day)

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TABLE IV
COST BREAKDOWN OF PV POWER PLANT FOR DIFFERENT LOCATIONS

Location	Asia (Malaysia)		Europe (Turkey)		Africa (Algeria)	
Costs	Cost (M$)	Share (%)	Cost (M$)	Share (%)	Cost (M$)	Share (%)
PV module	1.003	47.63	0.995	45.80	0.977	45.04
Inverter	0.164	7.81	0.126	5.80	0.175	8.06
Structure, land and devices	0.587	27.87	0.703	32.35	0.675	31.12
Maintenance	0.351	16.69	0.348	16.05	0.342	15.79
Total	2.107	100	2.173	100	2.170	100

As illustrated in Table III, the selected inverter for the optimized PV plant is completely different in terms of rated power and number. However, INV5 which uses 1.645 MW is selected for the case of Asia (Malaysia), in Europe (Turkey) is INV3 and presents a rated power of 630 kW, and in Africa (Algeria), INV4 is selected uses 875 kW. The number of installed inverters for 1.5 MW PV plant rated power is found equal to one in Asia (Malaysia) with two in Europe (Turkey) and Africa (Algeria) but not the same inverters rated power since the PV plant in Europe (Turkey) requires low rated power inverter due to the lowest energy production in winter as discussed earlier. The optimal values of PV modules connected in series (N_s) and parallel (N_p) are affected by the selected inverter in each location.

In real situations, the economic parameters have different values based on the selected location. However, in this research, the economic parameters of the PV plant were the same for all locations to study only the location impact. The cost breakdown of the PV power plant for different locations is illustrated in Table IV. Based on the obtained results, the equipment costs remain similar for the three locations and the PV modules cost is approximately half of the PV plant total cost while the inverter cost is around 8 %. As a result, the sizing ratio R_s of the PV power plants has different values for the three locations. The obtained sizing ratio is high in Europe (Turkey) and is equal to 1.165, which means that the PV power plant is quite oversized (i.e., $R_s > 1$) to capture more PV energy under weak solar irradiance conditions especially in winter, and to increase the PV inverter utilization. However, in Asia (Malaysia) and Africa (Algeria), the sizing ratio is 0.839 and 0.759, respectively due to the high solar irradiance during the year.

In Table III, annual PR values for each location are reported. The average annual PR is higher than 80% in each location. PR of the PV plant in Africa (Algeria) is the best and its value is about 87%. The worst PR is measured for the PV plant in Europe (Turkey), although it is just approximately 80%. Based on the PR metrics, it is evident that the location has a significant impact on PV plant performance.

Due to the significant difference in tilt angle between the PV power plants in the locations under study, which is equal to 11°, 26°, and 20° respectively. The occupied land, total PV modules area excluding land, and total PV modules for each location are illustrated in Fig. 5, Fig 6 and Fig. 7, respectively. As a result, the GCR value for the PV plant in Asia (Malaysia) is equal to 43.92%, Africa (Algeria) is 40.48%, and Europe (Turkey) is equal to 38.95 %. It can be observed that the land occupation for the PV plant is much higher in Europe (Turkey) and lower in Asia (Malaysia) due to the PV module tilt angle and inter-row spacing.

Energy losses for each 1.5 MW PV plant are shown in Table III for the whole year. The worst PV plant yearly loss value is measured in Europe (Turkey) with approximately 12 % of the total energy generation of the PV plant. The annual energy losses are much better and in the range of 8% for both PV plants in Africa (Algeria) and Asia (Malaysia). It is noticed that high energy production is not proportional to the electrical losses; PV plants in Africa (Algeria) produced a high amount of energy with only 8% of losses, while in Europe (Turkey) less energy production with more energy losses of about 12%.

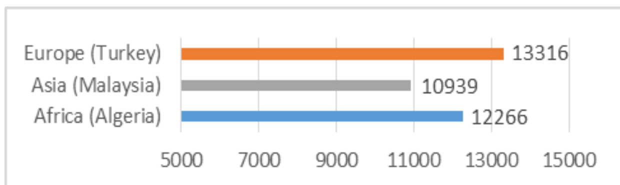

FIGURE 5. **Occupied land (m²) by the PV power plant for all locations.**

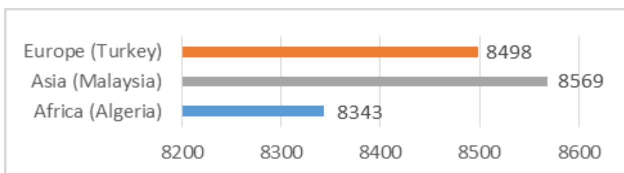

FIGURE 6. **Total PV modules area (m²) excluding land for all locations.**

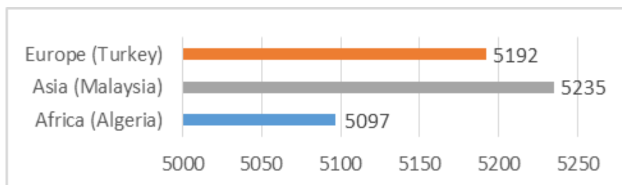

FIGURE 7. **Total number of installed PV modules for all locations.**

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B. METEOROLOGICAL DATA EFFECT

The impact of the variation of solar irradiance, ambient temperature, and wind speed on the PV power plant optimized design is investigated. For this purpose, the meteorological data have been changed hourly from -25% to 25%. The optimized design of the PV plant is evaluated by the variation of each factor independently. Minimum LCOE is set as an objective function to be achieved and, the PV plant rated power is 1.5 MW taking the case of Europe (Turkey).

1) SOLAR IRRADIATION

The variations in solar irradiance can affect the optimized design and performance of the PV power plant. The results of the optimal design variables for each variation in solar irradiance from -25% to 25% are illustrated in Table V. The increase and decrease in solar irradiance lead to different optimal design values, which means that the PV plant should be re-designed. The PV module type is the same for all cases. However, the inverter type should be replaced from INV3 to INV2 in low solar irradiance and from INV3 to INV5 in high solar irradiance to achieve the lowest LCOE, as well as the number of series (N_s) and parallel (N_p) PV modules connections should be modified according to the selected inverter. The rest of the design variables are almost the same for all cases.

The performance of the PV plant is affected by the variations of the solar irradiance as shown in Figs 8-13. The obtained results show that the objective function value is affected. An increase in solar irradiance level leads to high energy production, which results in low PV plant LCOE and vice versa. The PV plant sizing ratio has the best values in the case of a high amount of available solar irradiance (R_s<1). In contrast, an oversizing PV plant can be obtained in case of a low amount of available solar resources (1>R_s>1.6). The performance ratio of the PV plant is improved significantly due to the increase in solar radiation levels. The GCR has the same values even the levels of the solar irradiance are changed significantly; this is due mainly to the tilt angle design variable that has the same value for all cases. The PV plant's yearly energy loss value is proportional to the solar irradiance.

2) AMBIENT TEMPERATURE

The hourly variation of ambient temperature from -25% to 25% is considered. As illustrated in Table VI, the optimal design values are the same despite the increase and decrease of hourly ambient temperature. For locations with different ambient temperature profiles and the same solar irradiance, the PV plant optimal design can be similar. However, the PV plant's objective function is affected. Increasing the ambient temperature leads to a small decrease in the PV module output power which affects the PV power plant energy production and result in increasing LCOE value and vice versa. On the other hand, it is noticed that the variation of the ambient temperature levels has a weak impact on the PV power plant performance.

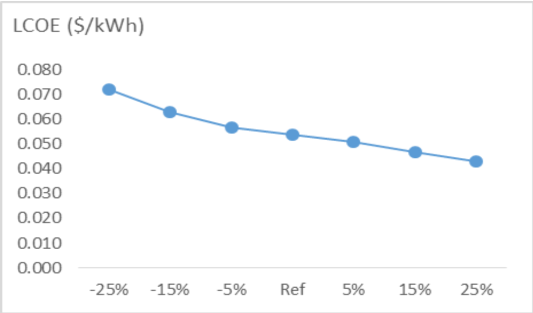

FIGURE 8. LCOE optimum values for different solar irradiance levels

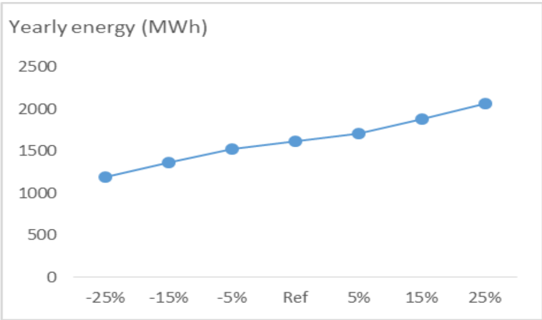

FIGURE 9. Annual energy production for different solar irradiance levels

TABLE V
PV PLANT DESIGN UNDER DIFFERENT SOLAR IRRADIANCE LEVELS

Design variables	-25%	-15%	-5%	Ref	5%	15%	25%
N_s	19	19	19	19	**18**	**25**	**24**
N_p	**143**	**129**	**138**	131	**134**	**67**	**200**
N_r	4	4	4	4	4	**2**	4
β	26	26	26	26	26	26	26
F_y	2.61	2.61	2.61	2.61	2.61	**1.40**	2.61
PV_i	PV3	PV3	PV3	PV3	PV3	PV3	PV3
INV_i	**INV2**	**INV2**	INV3	INV3	INV3	**INV2**	**INV5**
PV_{orien}	1	1	1	1	1	1	1
LCOE ($/kWh)	**0.072003**	**0.063206**	**0.056853**	0.053802	**0.051055**	**0.046932**	**0.042885**

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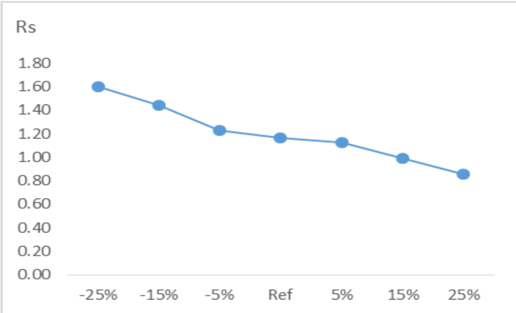

FIGURE 10. Sizing ratio optimum values for different solar irradiance levels

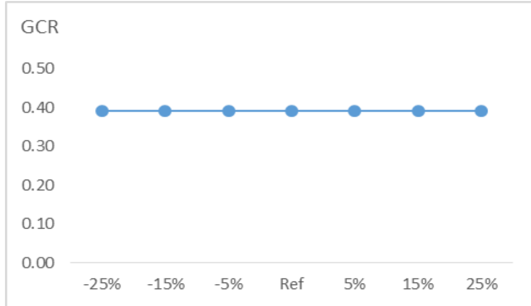

FIGURE 12. Ground cover ratio optimum values for different solar irradiance levels

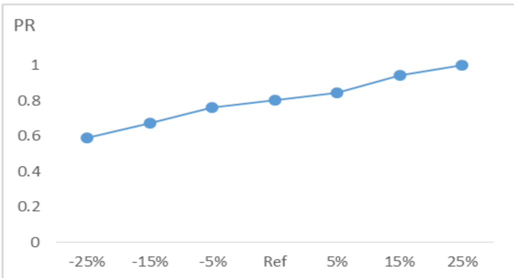

FIGURE 11. Performance ratio optimum values for different solar irradiance levels.

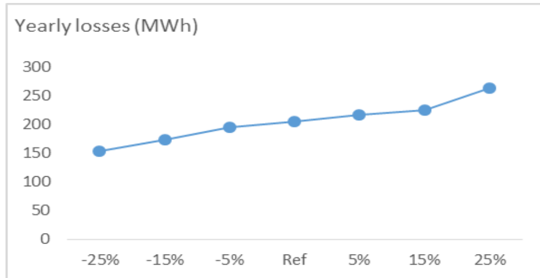

FIGURE 13. Yearly energy losses for different solar irradiance levels

TABLE VI
PV PLANT DESIGN UNDER DIFFERENT AMBIENT TEMPERATURE LEVELS

Design variables	-25%	-15%	-5%	Ref	5%	15%	25%
N_s	19	19	19	19	19	19	19
N_p	131	131	131	131	131	131	131
N_r	4	4	4	4	4	4	4
β	26	26	26	26	26	26	26
F_y	2.61	2.61	2.61	2.61	2.61	2.61	2.61
PV_i	PV3	PV3	PV3	PV3	PV3	PV3	PV3
INV_i	INV3	INV3	INV3	INV3	INV3	INV3	INV3
PV_{orien}	1	1	1	1	1	1	1
LCOE ($/kWh)	**0.053784**	**0.053791**	**0.053798**	0.053802	**0.053805**	**0.053813**	**0.053820**
Yearly energy (MWh)	1616.75	1616.48	1616.24	1616.13	1616.00	1615.78	1615.55
Rs	1.1655	1.1655	1.1655	1.1655	1.1655	1.1655	1.1655
PR	0.80259	0.80248	0.80237	0.802	0.80227	0.80216	0.80205
GCR	0.38952	0.38957	0.38958	0.38958	0.3896	0.3896	0.3896
Yearly losses (MWh)	205.8523	205.8296	205.807	205.7946	205.7843	205.7616	205.7389

3) WIND SPEED

The optimized design of the PV power plant is evaluated by changing the hourly wind speed from -25% to 25%. The obtained results are shown in Table VII. The design values for all cases are similar. It is noticed that the objective function changes from one case to another according to the wind speed level. In the case of increasing the wind speed, the PV cell temperature decreases and leads to an increase in the PV modules output power which results in low PV plant LCOE and vice versa. For all locations with different wind speed levels and the same solar irradiance, the PV plant's optimal design can be similar meaning that it is not necessary to re-design the PV plant. It can be seen from the results that the wind speed variation did not affect the PV plant performance.

C. AVAILABLE LAND EFFECT

To evaluate the effect of the available land on the PV power plant optimized design, available PV plant land is changed from -30% to 30% of the initial installation area of the PV plant which is equal to 15886 m^2. LCOE is set as an objective function to be achieved, taking the case of Africa (Algeria). The variation impact of the available land on the

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optimum design parameters of the PV power plant is investigated. The area variation can be achieved by reducing or increasing the available land. The reason behind this variation is to show the correlation between the area and the PV plant optimum design. The available land variation can be required anytime and for both cases before or after installing the PV plant. The obtained results are illustrated in Table VIII.

TABLE VII
PV PLANT DESIGN FOR DIFFERENT AVAILABLE LAND

Design variables	-30%	Ref	+30%
N_s	**22**	23	**24**
N_p	**74**	98	**66**
N_r	3	3	**2**
β	20	20	20
F_y	1.5268	1.5268	**1.0191**
PV_i	PV3	PV3	PV3
INV_i	**INV3**	INV4	**INV3**
PV_{orien}	1	1	1
LCOE ($/kWh)	0.030496	0.030181	0.030261
Yearly energy (MWh)	2071.72	2876.24	3728.89
Rs	0.76232	0.75992	0.74171
PR	0.87025	0.871	0.87007
GCR	0.40431	0.40482	0.40554
Yearly losses (MWh)	175.7516	240.8513	317.1751

The PV power plant should be re-designed. The total number of series (N_s) and parallel (N_p) PV module connections has been changed, the number of PV module lines in each row (N_r) is changed in case of increasing the available land to 30%, and the type of selected inverter has been modified from type INV4 to Type INV3. This research takes into account the shape and size in designing the PV power plant to increase the financial benefits. The sizing ratio, performance ratio, and ground cover ratio have the almost same values even changing the available land. In contrast, the produced energy and energy losses changed based on the PV plant area.

D. PV MODULES AND INVERTERS EFFECT

This case examines the importance of the PV module in building the PV power plant. LCOE is set as an objective function to be achieved, taking the case of Europe (Turkey) for a capacity of 1.5 MW. The optimization process is executed, excluding the PV3 from the list of candidates. It is found that the LCOE is affected and becomes much higher compared to the PV plant using PV3, as illustrated in Table IX.

From an economic point of view, it affects the financial benefit of the PV power plant since the LCOE increased. Technically, among the design variables of the PV plant, only (N_s) and (N_p) are affected and have new values since the PV module PV1 has characteristics different from those of PV3. On the other hand, the PV modules have not affected the PV plant performance since all the PV modules used in this optimization methodology have approximately the same efficiency.

To demonstrate the effect of the inverter in the PV power plant performance and optimized design parameters, the optimization procedure is executed without using inverter INV5. LCOE is set as an objective function to be achieved, taking the case of Asia (Malaysia) for a rated power of 1.5 MW. The results shown in Table X reveal that the LCOE is increased using INV2, which decreases the financial benefits of the PV plant. The selected inverter INV2 used 500 kW and led to different values of the design variables of the PV plant. It is noticed that using INV2; the PV plant sizing ratio changed from 0.83 to 0.92, annual output energy reduced from 2261.34 MWh to 2200.02 MWh. In contrast, the yearly energy losses declined from 191.146 MWh to 183.58 MWh.

TABLE VIII
PV PLANT DESIGN UNDER DIFFERENT WIND SPEED LEVELS.

Design variables	-25%	-15%	-5%	Ref	5%	15%	25%
N_s	19	19	19	19	19	19	19
N_p	131	131	131	131	131	131	131
N_r	4	4	4	4	4	4	4
β	26	26	26	26	26	26	26
F_y	2.6103	2.6103	2.6103	2.6108	2.6108	2.6108	2.6108
PV_i	PV3	PV3	PV3	PV3	PV3	PV3	PV3
INV_i	INV3	INV3	INV3	INV3	INV3	INV3	INV3
PV_{orien}	1	1	1	1	1	1	1
LCOE ($/kWh)	**0.053805**	**0.053804**	**0.053802**	0.053802	**0.053801**	**0.053800**	**0.053798**
Yearly energy (MWh)	1616.00	1616.04	1616.08	1616.13	1616.16	1616.20	1616.24
Rs	1.1655	1.1655	1.1655	1.1655	1.1655	1.1655	1.1655
PR	0.80227	0.80229	0.80231	0.802	0.80233	0.80235	0.80237
GCR	0.3896	0.3896	0.3896	0.38958	0.38958	0.38958	0.38958
Yearly losses (MWh)	205.7837	205.7885	205.7932	205.7946	205.798	205.8028	205.8075

TABLE IX
EFFECT OF PV MODULE ON PV PLANT DESIGN

Design variables	Ref	Optimization excluding PVi= 3
N_s	19	**25**
N_p	131	**104**
N_r	4	4
β	26	26
F_y	2.6108	2.6092
PV_i	PV3	**PV1**
INV_i	INV3	INV3
PV_{orien}	1	1
LCOE ($/kWh)	0.053802	**0.054683**
Yearly energy (MWh)	1613.55	1616.13
Rs	1.1556	1.1655
PR	0.80253	0.802
GCR	0.38938	0.38958
Yearly losses (MWh)	205.6319	205.7946

TABLE X
INVERTER EFFECT ON PV PLANT DESIGN.

Design variables	Ref	Optimization excluding INVi= 5
N_s	24	**16**
N_p	195	**98**
N_r	5	**4**
β	11	11
F_y	1.4196	**1.1357**
PV_i	PV3	PV3
INV_i	INV5	**INV2**
PV_{orien}	1	1
LCOE ($/kWh)	0.037281	**0.037501**
Yearly energy (MWh)	2261.34	2200.02
Rs	0.83927	0.92512
PR	0.838	0.83927
GCR	0.43925	0.43911
Yearly losses (MWh)	191.146	183.5878

E. OBJECTIVE FUNCTION EFFECT

Three objectives are taken into account, namely minimum cost, maximum energy generation, and minimum LCOE. Taking the case of Asia (Malaysia), the PV plant is designed for a capacity of 1 MW to investigate the effect of the objective function on the design variables of the PV power plant. The results are illustrated in Table XI. It can be seen that the design variables of the PV plant are affected by the variation in the objective function. Additionally, the sizing ratio for maximum energy is equal to 0.77, whereas in the case of LCOE and minimum cost objectives is much higher and reaches 0.94 and 0.93, respectively. Moreover, the ground cover ratio is the lowest using the maximum energy objective function with a value of 37%. In contrast, it is higher and equal to 43% for the case of LCOE and minimum cost objective functions.

The land occupied by the PV plant is much higher based on maximum energy optimization and reaches 11.245 m^2 and required less land in the case of using LCOE and minimum cost with 7.365 m^2 and 7.163 m^2, respectively. The difference in ground cover ratio shows that the maximum energy objective function consumes 24% more land compared to the case of LCOE and minimum cost. Furthermore, among the three objective functions, the use of LCOE in designing the PV plant is economically more profitable. The performance ratio of the PV plant for the three objectives is the same and equal to approximately 0.84.

TABLE XI
COMPARISON OF PV POWER PLANT DESIGN RESULTS BY OBJECTIVE FUNCTIONS CONSIDERED

Design variables	Min LCOE	Max energy	Min cost
N_s	**19**	**20**	**24**
N_p	**84**	**58**	**66**
N_r	**4**	**3**	**2**
β	11	11	11
F_y	**1.1357**	**3.966**	**0.567**
PV_i	PV3	**PV4**	PV3
INV_i	INV2	INV2	INV2
PV_{orien}	1	**2**	1
LCOE ($/kWh)	**0.037706**	0.042392	0.037807
Max energy (MWh)	1522043.849	**1708966.758**	1477895.088
Min cost (M$)	1434744.439	1811146.986	**1396858.77**
Rs	0.94164	0.7772	0.93456
PR	0.83928	0.8401	0.83926
GCR	0.43891	0.37546	0.43853
Yearly losses (MWh)	126.9964	141.8011	123.3607

F. OPTIMISATION TECHNIQUES EFFECT

Applying several optimization techniques to design the PV power plant can help identify the optimal objective function through the comparison of the final results. To examine the algorithm's effect on the variation of the design variable of the PV power plant, the case of Europe (Turkey) with no rating power constraint to use all the available land is considered. In this study, single and hybrid with single objective function including, multi-verse optimizer, particle swarm optimization, hybrid particle swarm optimization, and grey wolf optimizer and hybrid cuckoo search-grey wolf optimization were applied. The LCOE is the objective function considered in this case. Table XII shows the obtained results of the optimal PV plant design. The optimal PV plant design variables are affected by the applied algorithm and the same for the optimal value of the objective function. The lowest LCOE is obtained using a hybrid CSGWO algorithm with 0.053773 ($/kWh). The optimization algorithm with high performance can contribute to increasing the system profit using the same design conditions.

TABLE XII
COMPARISON OF PV POWER PLANT DESIGN RESULTS BY ALGORITHMS USED

Design variables	MVO	PSO	PSOGWO	GWOCS
N_s	25	19	19	24
N_p	104	134	105	81
N_r	4	4	3	4
β	26	26	26	26
F_y	2.6092	2.6102	1.9569	2.6134
PV_i	PV1	PV3	PV3	PV3
INV_i	INV3	INV3	INV2	INV2
PV_{orien}	1	1	1	1
LCOE ($/kWh)	0.055496	0.054405	0.053836	**0.053773**

VII. ENVIRONMENTAL IMPACTS

Clean energy production from renewable resources and particularly PV power plants, have a positive impact on the atmosphere. Coal thermal power plants release a significant quantity of green-house gases like carbon dioxide (CO_2), nitrogen oxide (NO_x), sulphur dioxide (SO_2), and Ash. The annual reduction of green-house gas emissions by composite (1.5 MW) PV plants for each location is shown in Table XIII. From the results, it is shown that the PV plant in Africa (Algeria) has caused an emission saving of 2818.72 tons CO_2, 35.67 tons SO_2, 74.49 tons NO_x, 195.58 tons Ash from the atmosphere per annum, the PV plant in Asia (Malaysia) has caused a total annual reduction of about 2216.12 tons CO_2, 28.04 tons SO_2, 58.57 tons NO_x, and 153.77 tons Ash, and the PV plant in Europe (Turkey) has caused an annual reduction of 1583.81 tons CO_2, 20.04 tons SO_2, 41.86 tons NO_x, and 109.9 tons Ash.

TABLE XIII
ANNUAL REDUCTION OF GREEN-HOUSE GASES EMISSIONS BY COMPOSITE (1.5 MW) PV PLANTS.

GHG	Emission (tons/kWh)	Total annual reduction (tons) every year			Reference
		Africa (Algeria)	Asia (Malaysia)	Europe (Turkey)	
		2876240.6 kWh	2261344.2 kWh	1616134.6 kWh	
CO_2	980.10^{-6}	2818.72	2216.12	1583.81	[40], [41]
SO_2	$1.24.10^{-6}$	35.67	28.04	20.04	[42]
NO_x	$2.59.10^{-6}$	74.49	58.57	41.86	[42]
Ash	68.10^{-6}	195.58	153.77	109.9	[42]

TABLE XIV
SUMMARY OF PV PLANTS DESIGN METHODS.

N	Year	Method	Target	Country	Reference
1	2005	Numerical	Maximum energy	USA	[43]
2	2006	Evolutionary Programming	NPV	Spain	[7]
3	2009	GA	NPV	Greece	[8]
4	2010	PSO	NPV	Greece	[44]
5	2010	Multi-Objective PSO	NPV	Greece	[10]
6	2011	GA	Excess factor (EF)	Malaysia	[45]
7	2011	GA	LCOE	Greece	[46]
8	2012	Evolutionary Programming	NPV	Malaysia	[47]
9	2013	GA	LCOE	Denmark	[11]
10	2014	GA	Maximum energy	France	[48]
11	2014	Master-Slave and Dynamic Demes	LCOE	Greece	[12]
12	2016	PVSOL software	NPV	Cyprus	[49]
13	2016	GA	LCOE	India	[14]
14	2017	Tabu Search (TS)	1) Payback time 2) Maximum energy 3) Maximum benefits	Canada	[17]
15	2017	Mathematical model	NPV	Croatia	[50]
16	2017	GA	LCOE	Turkey	[15]
17	2018	Multi-objective GA	1) Output energy 2) Investment payback time 3) Energy payback time	France	[51]
18	2019	Binary linear programming	NPV	USA	[52]
19	2020	GA	Internal rate of return (IRR)	Hungary	[53]
20	2020	Hybrid GWO-SCA	1) LCOE 2) Maximum energy	Algeria	[19]

VIII. SUMMARY OF PV PLANT DESIGN

Different targets have been set to achieve the PV plant optimal configuration, including LCOE, NPV, payback period, and harvested energy. Table XIV summarizes the PV power plant design methods. It is observed that artificial intelligence such as GA, and metaheuristic methods, such as PSO, have been largely applied by researchers due to their advantages. The effect of variation in solar irradiance, ambient temperature, and available area on the PV system is investigated in [17]. However, the proposed model omitted a critical aspect related to the optimal placement of the PV modules, which is partial shading. The study missed considering the inter-row distance between adjacent rows as a design variable which leads to significant energy losses. In light of this, the impact of the key factors on the large-scale PV plant optimized design investigated in this research has not been studied in previous studies which focused only on sizing methodology.

IX. CONCLUSION

The design of the PV power plant has a significant influence on optimum performance and financial benefits; otherwise, technical and economic issues can be faced if not appropriately designed. The present study assessed the impact of various key factors on the optimized design of the PV power plant since such factors can lead to re-design the PV power plant. From this research, some conclusions can be argued:

1. The PV plant design is investigated considering different locations around the world. The geographic location has a significant impact on the PV power plant's optimal design. According to optimized PV plant results, the design differs for the three sampled countries despite using the same PV plant capacity, available area, costs, and components. This leads to the conclusion that an optimum PV plant design in one location might not be effective for another location and can lead to high financial risks. The PV plant should be re-designed according to the characteristic of the location, as demonstrated in this study. The objective function is also affected.
2. The variations in the level of solar irradiance, ambient temperature and, wind speed from -25% to +25% were performed separately to investigate the impact of such variation on the optimized PV plant. It is observed that the increase and decrease in solar irradiance level can lead to different optimal design values, which requires to re-design the PV plant. This can be applicable to locations with different solar irradiance profiles. Besides, for different levels of ambient temperature and wind speed, the PV plant re-design is not required. However, the objective function is significantly affected.
3. The correlation between the available area and the PV plant optimum design is investigated considering area changes of -30% and +30% since it can be required before or after installing the PV plant. It is observed that the PV power plant should be re-designed according to the available area to increase the financial benefits of the PV plant.
4. The type of PV module and the size of the inverter have a significant effect on PV plant performance. In the case of excluding the optimally selected PV module and inverter obtained during the initial optimization process, the new optimal PV plant design is changed. Also, changing such components can significantly affect the LCOE. Hence, the optimal choice of PV module and inverter in designing the PV plant can lead to avoiding financial risks. The inverter used in the PV power plant has no relation with the occupied area, and the number of PV modules installed, in contrast to the PV module.
5. Using different objective functions to optimally designing the PV power plant including, minimum LCOE, maximum annual energy, and minimum cost, result in entirely different optimized designs. The minimum LCOE based optimization objective function achieved better financial benefits for the PV plant.
6. Single and hybrid algorithms with single objective function including MVO, PSO, hybrid PSOGWO and, finally, hybrid CSGWO techniques were applied. All applied algorithms resulted in different optimized PV plant designs. Hence, the effectiveness of the optimization technique can contribute to increasing the financial benefits of the PV plant.
7. Based on the technical analysis, the PV power plant performance parameters were significantly changed due to the variation of most factors.
8. It is estimated that in the case of the 1.5 MW PV power plant installed in Africa (Algeria), Asia (Malaysia), and Europe (Turkey), the total carbon emissions will be saved 2818.72, 2216.12, and 1583.81 tons of CO_2 respectively, from the atmosphere per year.

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